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Relative sea-level change and climate change in the Northeastern Adriatic during the last 1.5 ka (Istria, Croatia)

Sanja Faivre [a], [*], Tatjana Bakran-Petricioli [b], Jadranka Barešić [c], Davor Horvatić [d], Kita Macario [e]

[a] University of Zagreb, Faculty of Science, Department of Geography, Marulićev trg 19/II, 10 000 Zagreb, Croatia
[b] University of Zagreb, Faculty of Science, Department of Biology, Rooseveltov trg 6, 10 000 Zagreb, Croatia
[c] Ruđer Bošković Institute, Radiocarbon Laboratory, Bijenička 54, 10 000 Zagreb, Croatia
[d] University of Zagreb, Faculty of Science, Department of Physics, Bijenička 32, 10 000 Zagreb, Croatia
[e] Departamento de Física, Universidade Federal Fluminense, Av. Gal. Milton Tavares de Souza, s/n, Niteroi, 24210-346, RJ, Brazil

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ABSTRACT

A new high-resolution relative sea-level (RSL) reconstruction is presented for the past 1500 years based on four bio-constructions formed by alga *Lithophyllum byssoides* (algal rims). Two algal structures have been studied on the southern (Premantura site) and two on the eastern Istrian coast (Uboka and Brseč sites) in the Northeastern Adriatic. The data from the algal rims (47 radiocarbon data points) enabled the distinction of four major phases of RSL change which corresponds to periods of climate change. RSL between AD 400 and 800 during the Dark Ages Cold Period (DACP), was almost stable. After AD 800, during the Medieval Climate Anomaly (MCA) the RSL increased up to ~0.8 mm/yr. The following Little Ice Age period, (LIA) interval I (AD 1400 till 1600) is again characterised by RSL stability (RSL slowed down) which allows the rims at the southern coast to reach the width of ~40–80 cm at their uppermost part and up to 20 cm for those along the eastern coast. Between AD ~1600 and 1750, during the colder LIA II interval, algal rims do not form, as LIA II is assumed to be a period of RSL fall. Algal rims reveal that from the second part of the 19th century the RSL rose by 13–15 cm at the Premantura location and around 10 cm at the Brseč and Uboka areas, providing rates between 1 and 0.7 mm/yr respectively for the Current Warm Period (CWP).

The sea-level trends were quantitatively defined using an Errors-In-Variables Integrated Gaussian Process (EIV-IGP) model, with full consideration of the available uncertainty. Following correction for the total land-level change (assumed to be around −0.4 mm/yr), four successive trends in sea-level change were confirmed. Sea-level dropped during the DACP at a mean rate of −0.4 mm/yr and increased to 0.5 mm/y as a consequence of Medieval warmth. Thereafter it was relatively stable during LIA I, fell up to −0.1 mm/yr during LIA II interval and has been slowly rising again during the CWP. Moreover, *L. byssoides* $\delta^{18}O$ records show that these periods of sea-level changes are consistent with changes in temperature and thus with periods of rapid climate change.

1. Introduction

The late Holocene (last 2–3 ka) is the most intensively studied period in palaeo-sea-level research (Gehrels et al., 2011). During the last two decades, this period has also been increasingly studied along the eastern Adriatic (e.g. Fouache et al., 2000; Faivre and Fouache, 2003; Benac et al., 2004; Pirazzoli, 2005, Antonioli et al., 2007; Florido et al., 2011; Furlani et al., 2011a, 2011b, 2014; Faivre et al., 2010a,b, 2011a,b; Shaw et al., 2018; Marriner et al., 2014; Evelpidou et al., 2014a, Evelpidou and Pirazzoli, 2017; Vilibić et al., 2017; Faivre and Butorac, 2018). Sea-level curves are obtained using various methods, from land and sea records, and are based on different markers (geomorphological, sedimentological, archaeological, historical and biological/ecological) which are often combined or used together (e.g. Antonioli et al., 2011; Vacchi et al., 2016).

Archaeological markers were one of the first used along the eastern Adriatic in recognising relative sea-level (RSL) change.

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[*] Corresponding author.
E-mail address: sfaivre@geog.pmf.hr (S. Faivre).

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Based on submerged archaeological remains in Istria and Dalmatia in the 18th century, Donati (1750) concluded that sea-level rise had occurred along the eastern Adriatic coast from the Antiquity. Geomorphological markers were also recognised as good RSL indictors, i.e. tidal notches in the Dubrovnik area as first described by Suess (1885–1908). Andrijašević (1910) demonstrated the importance of active tidal notch formation in the explanation of sea-level variations. Observable active tidal notches are proof of actual long-term RSL stability while submerged notches are the result of tectonic and possible co-seismic activity. Based on these observations Andrijašević (1910) contrary to Penck (1894), assumed that general submergence of the whole eastern Adriatic coast during historic times was not possible. Submerged archaeological structures in Istria related to geological properties of the area, allowed Gnirs (1908) to conclude the occurrence of a 2 m RSL rise during the last 2000 years. Numerous investigations of submerged archaeological remains have since followed. Likewise, Degrassi (1955) suggested that the sea-level in Istria during Roman times was 1.5 m lower than present, while Vrsalović (1979) and Kozličić (1986) proposed a rise of 2 m.

Recent studies use the submerged archaeological remains with greater precision and consistency (Antonioli et al., 2007; Fouache et al., 2011; Rousse et al., 2013) estimating that the RSL in Istria during Roman times was ~1–1.5 m lower than today. During the last 20 years, much attention has been also paid to the enigmatic submerged tidal notches which in Istria are generally found 50–80 cm below present mean sea-level (MSL) (Fouache et al., 2000, 2005; Faivre and Fouache, 2003; Antonioli et al., 2004, Benac et al., 2004, Furlani et al., 2011a, 2014). Nevertheless, as the submerged tidal notches cannot be directly dated, they have been studied in combination with archaeological (e.g. Fouache et al., 2000, 2005, 2011; Faivre and Fouache, 2003; Antonioli et al., 2007; Faivre et al., 2010a, 2010b), and sedimentological markers (Faivre et al., 2011a).

According to the results obtained, the notch formation phase was attributed by most scholars to the Roman period (Fouache et al., 2000; Faivre and Fouache, 2003). On the basis of recent lowering rates, Furlani et al. (2009) suggested a formation period spanning ~500 ± 100 years. The processes and event(s) responsible for the quasi-regional subsidence have generated significant debate as according to Boulton and Stewart (2015), their genesis is quite challenging in the traditionally assumed submergence domain, as this would imply particularly complex tectonic histories.

In order to provide more precision and better accuracy of 2 ka sea-level curves, the latest research along the eastern Adriatic has centred on bio-constructions as sea-level markers (Faivre et al., 2013), as fossil bio-constructions have proven to be precise sea-level indicators in microtidal environments (Laborel et al., 1994; Morhange, 1994; Laborel and Laborel-Deguen, 1996, 2005; Laborel, 2005). Their vertical precision (±10 cm) in a relatively sheltered position, comes from the restricted environmental conditions of the alga *L. byssoides* that have a very narrow vertical range closely associated to mean sea-level (MSL). The alga creates the highest biogenic build-up in the Mediterranean (Rovere et al., 2015) which can be dated using ^{14}C.

Within the intertidal zone along rocky carbonate coastlines, bioconstructional activity of coralline alga is limited in scale, location and permanence, compared with the skeletal framework of coral reefs, but could make a very important contribution to coastal geomorphology and ecology (Spencer and Viles, 2002). Reefs made by coralline red algae (such as *Lithophyllum*) have been found in many tropical and extratropical locations (Spencer and Viles, 2002; Ingrosso et al., 2018) but their importance as a sea-level and palaeoenvironmental indicator is crucial outside the (tropical) coral reef belt, e.g. in the Mediterranean (Sechi et al., 2018).

The study of the biological sea-level markers along the eastern Adriatic coast started in 2009 (Faivre et al., 2010a) with the aim of restraining the error bars and obtaining more accurate results for comparison of different sea-level indicators. The first investigations of algal rims were done in the Central Adriatic on the islands of Vis, Ravnik and Biševo, which showed that bio-constructions such as *Lithophyllum* rims are excellent high precision sea-level indicators. Their morphology and ^{14}C age showed that they could also be related to the distinguished periods of rapid climate change (Faivre et al., 2013).

Here, we reconstruct late Holocene RSL change at high resolution using *Lithophyllum* rims from the Northeastern Adriatic (Istria). In order to study the relationship of RSL change to periods of rapid climate change, we conducted *L. byssoides* $\delta^{18}0$ analyses for the last 1.5 ka which can provide an indirect measure of climatic changes and also of possible climatic impacts on marine ecosystems. To better understand the driving mechanisms of RSL change in the Northern Adriatic, an area particularly vulnerable to sea-level rise and storm surges (Kaniewski et al., 2016), we further correct the RSL record for the Glacial Isostatic Adjustment (GIA) effect and for the estimated land-level movements.

Furthermore, earlier studies provided evidence of the notch formation period, however, the chronological details of the notch's submersion (when and how the submersion actually occurred) are poorly understood. We propose to overcome these difficulties by studying tidal notches from the same sites and compare them to the evidence from algal rim chronology, as both algal rims and tidal notches form on rocky coast. In order to estimate the beginning of the recent RSL rise (the CWP) we also used new historical data.

2. Study area

Istria belongs to the North West part of the ancient Adriatic Carbonate Platform. This platform is composed of a thick carbonate deposit succession (3500–5000 m), occasionally more than 8000 m (Vlahović et al., 2002, 2005). The Istrian sequence consists predominantly of carbonate rocks ranging from Middle Jurassic (Late Dogger) to Eocene ages, with subordinate Middle Upper Eocene clastic rocks composed of flysch and calcareous breccias (Tišljar et al., 1998; Velić et al., 1995, 2003). The overlying Quaternary *terra rossa* and loess close the sequence.

With its massive morphology, Istria strongly differs from the other parts of the Croatian coastal areas. The geomorphological peculiarities can easily be discerned from the local colloquial names. The Red Istria - the southern and western Istrian erosional plain, named after the *terra rossa*, the Grey or Green Istria - in its central part, characterized by the strongly dissected Middle Upper Eocene flysch foothills, and the White Istria - in the eastern, north-eastern and northern Istria, characterized by karstified outcrops of “white” Cretaceous – Lower-Middle Eocene limestones. White Istria is represented by the mountain ridges of Ćićarija (1272 m) and Učka (1396 m), which are, together with the central flysch area, particularly strongly expressed in relief (Fig. 1). The Istrian coast follows this tripartite division: cliffs are formed in flysch in the north-west, a low lying limestone coast extending from Savudrija in the north-west to Plomin bay in the east, and a higher rocky limestone coast in the north-east. The geological and geomorphological properties of the Istrian peninsula were detailed in Faivre et al. (2011a).

Istria is not considered a seismically active area (Herak and Herak, 2004, 2006) as seismicity is shallow and earthquakes are located within the upper crust. The most important epicentral zone lies between Senj, Vinodol, Rijeka and Ilirska Bistrica (Herak et al.,

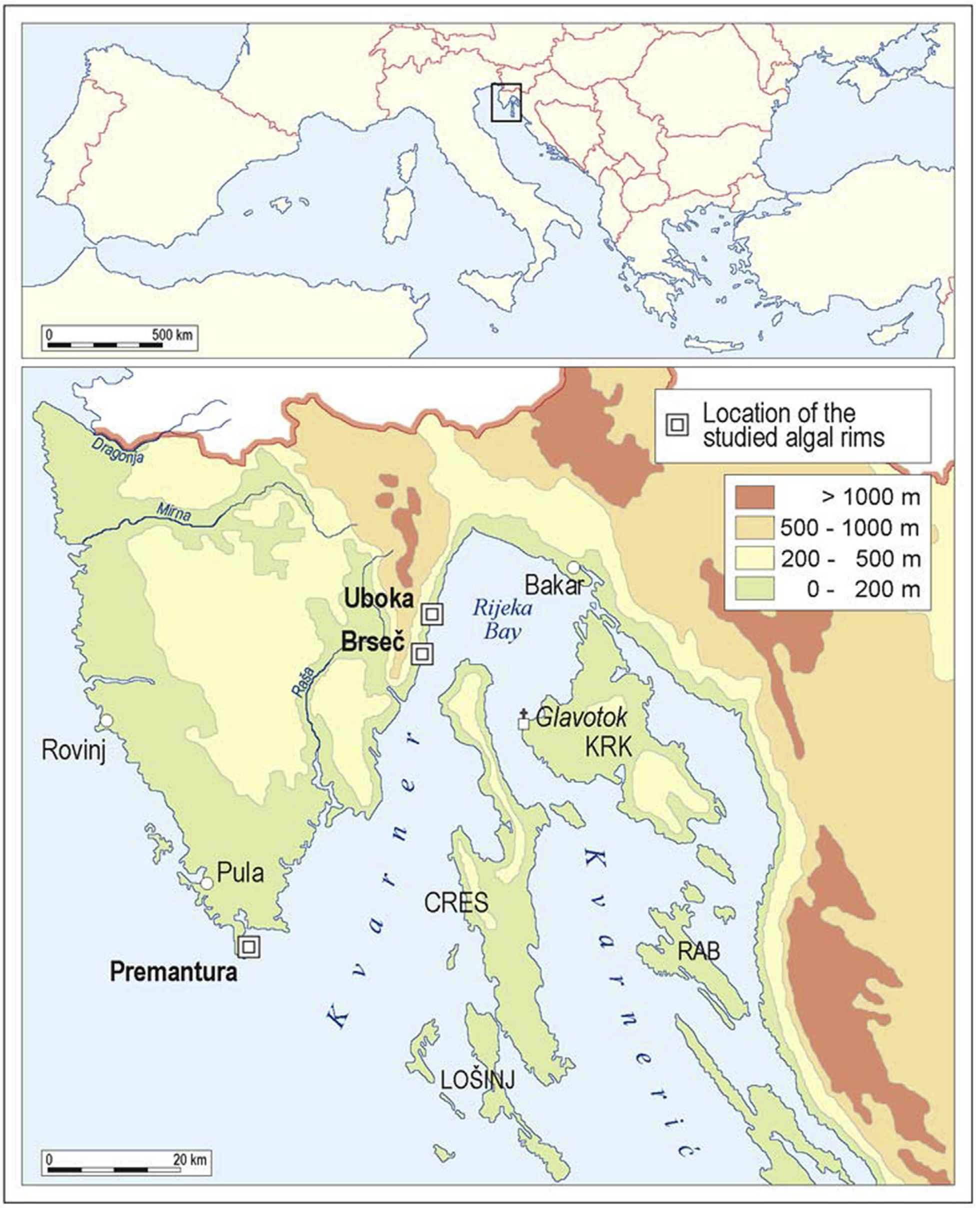

Fig. 1. The study area – location of the studied algal rims and the St. Mary's monastery and Church (Glavotok area).

2017). The Učka - Trieste fault zone (Fig. 2), at 1–3 km wide is the boundary fault between weakly and strongly deformed parts of the Adriatic microplate (Prelogović et al., 2003, 2004). Likewise, studied algal rims represent parts of two different structural units – two rims were studied on each side of the Učka-Trieste fault zone (on each structural unit) (Fig. 2).

3. The biological basis

Marine benthic organisms are finely adapted to very precise ecological conditions and this is manifested as biological zonation. Three particular biological zones can be distinguished: the supralittoral (wave splash zone), the mediolittoral (tidal zone) and the infralittoral (subtidal) zone (Pérès, 1982). Many regional and local differences due to biogeography, tides, direction and intensity of the prevailing winds, water temperature and other oceanographic factors further shape these zones (Laborel et al., 1994). The *Lithophyllum* rim is an organogenic calcareous protrusion that grows out from steep rocky surfaces slightly over mean sea-level (MSL) (Laborel et al., 1994; Faivre et al., 2013).

Along the eastern Adriatic they primarily develop in the less agitated parts of the exposed coasts as generally proposed by Pérès and Picard (1952). Consequently, they are best developed in the inlets of exposed coasts because the organic construction requires the strong mixing of water, but not too strong wave impact (Adey and MacIntyre, 1973). Water turbulence and wave-pumping of water through the bioconstructions may also aid the lithification processes (Spencer and Viles, 2002). The biogenic structure therefore grows in thickness always covered by another layer of encrusting coralline algae. The infralittoral part of the rim is covered by upright bushy, articulated coralline algae including *Jania rubens* and *Corallina* spp. The bioconstructions, although protecting the underlying rock surfaces, are themselves prone to erosion, primarily by bioeroders such as clionid sponges and the boring

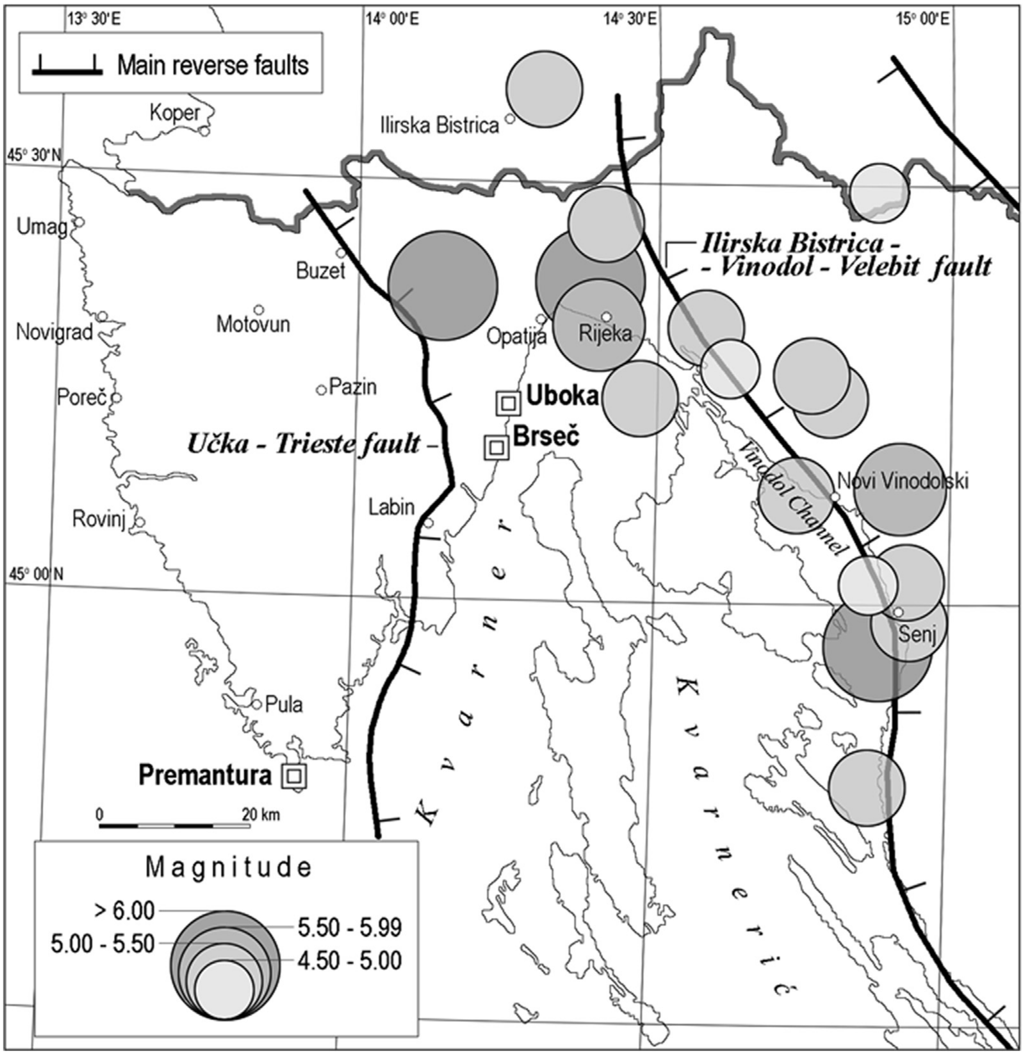

Fig. 2. The main structural units (after Prelogović et al., 2004) with earthquake epicentre locations in Istria and the Kvarner area from 1500 to 2003, (mainshocks with magnitude > 5.0 or with intensity > VII MCS scale after Herak and Herak (2004) and Herak et al. (2005)).

bivalve *Lithophaga lithophaga* (Spencer and Viles, 2002). Despite possible strong bioerosion as evidenced by Morhange (1994) in the Western Mediterranean, well-developed fossil *Lithophyllum* formations could be preserved after submergence (Laborel et al., 1994; Faivre et al., 2010a, 2013).

4. Material and methods

4.1. Field work

Four algal rims have been studied at three locations on the southern and eastern Istrian coast (Fig. 1). The algal rims were precisely measured, mapped and sampled for ^{14}C dating from 2011 to 2017. Vertical sections were excavated with a hammer and chisel. *Lithophyllum byssoides* have a very narrow vertical range closely associated to mean sea-level (MSL). Therefore, levelling was done by direct measurements of the vertical distance between the outer edge of the upper level algal rim, taken as the reference datum, and the centre of the broken section as explained in Laborel (1986) and Laborel et al. (1994). The sea water level at the time of sampling was also taken into account (data obtained from the Hydrographic Institute of the Republic of Croatia and from the Faculty of Science, Department of Geophysics). Consequently, all sample depths have been corrected to the nearest tide gauge stations (Rovinj and Bakar) and expressed according to the Croatian national datum (Domijan et al., 2005).

Biological sea-level markers are not perfect horizontal lines; they are naturally warped even over short distances, due to the local variations of hydrodynamics and morphology. At the Premantura and Uboka areas, *Lithophyllum* rims have developed in the more inner part of the exposed coasts, while at the Brseč area the rim is more directly exposed.

The vertical range of living *Lithophyllum* thalli at the study area is around 20 cm, so the total error is estimated at ±10 cm. At the Brseč area due to the exposed position, which may influence the elevation, the uncertainty is estimated as ±15 cm.

All studied *Lithophyllum* rims occur on limestone, though generally their development is not restricted to calcareous substrates. The growth rate of the living thalli is relatively rapid, up to 3 cm in diameter per year (Boudouresque et al., 1972), but the evolution from an incipient algal population to a mature rim with a hardened core is a long process and does not happen everywhere. The inner structure of the studied algal rims revealed the consolidated layers of dead thalli. The core has a multilayered structure with numerous discontinuities. Among the lamellar excrescences of *Lithophyllum* thalli, numerous populations of living bivalves *Mytilaster lineatus* (Gmelin, 1791) and *Lasaea adansoni* (Gmelin, 1791) were noted in the living part of the algal rim. Both species are also found inside the old segments of the algal rims which have been sampled and dated to crosscheck with the data from the *Lithophyllum byssoides* (alga). Consequently, the RSL reconstruction is based on 47 data points (35 algae and 12 shells) that are unevenly distributed through time and have a unique combination of temporal and vertical uncertainty.

Tides in the Adriatic are of semidiurnal type. In the Northern Adriatic their amplitudes are higher than in the rest of the Mediterranean (Tsimplis et al., 1995). They are especially high primarily due to the near-resonant coupling of the equilibrium tide with the Adriatic topography through the co-oscillation with the Ionian and Eastern Mediterranean tides (Vilibić et al., 2005). In the study area the average tidal amplitude is 47.7 cm (data from the Rovinj tide gauge, Čupić, pers. comm.) and 24 cm at Bakar tide gauge (Pasarić, pers. comm.), relevant for the eastern Istrian coast.

4.2. Vertical land motion

The northern Adriatic coast is generally considered to be a subsiding environment (Pirazzoli, 2005; Antonioli et al., 2004, 2007; 2009; Shaw et al., 2018). In order to estimate the ongoing contribution of land-level change and identify climate driven sea-level trends, we applied corrections for crustal movements associated with the spatially variable and ongoing GIA.

The mean GIA trend in the Mediterranean Sea was calculated at 0.42 mm/yr (Tsimplis et al., 2013), while the predicted GIA values for the Adriatic were generally lower and varied between 0.125 and 0.375 mm/yr (e.g. Stocchi and Spada, 2009; Lambeck et al., 2011). Here, a constant rate of subsidence of 0.188 mm/yr (with no error) from Lambeck et al. (2011) was subtracted from the Premantura, Uboka and Brseč records. Such use of a constant rate is appropriate for this time period given Earth's rate of visco-elastic response (Peltier, 1996; Kemp et al., 2015). The new ICE-7G_NA (VM7) glacial-isostatic model of Roy and Peltier (2018) reveals slightly lower values, −0.25 m since 2 ka BP. The resulting records are termed “GIA-adjusted”. If the data for the reference period, AD 1400–1600 (a period of RSL stability clearly evidenced in the morphology of the algal rims and defined with numerous analysed data points) do not reach the MSL with GIA correction, additional corrections will be effected and termed “land-level adjusted” in order to try to distinguish and remove the total land movements.

4.3. Quantitative analyses of relative sea-level changes

The RSL changes reconstructed from the algal rims were quantified using an Error-In-Variables Integrated Gaussian Process (EIV-IGP) model (Cahill et al., 2015). The EIV-IGP model takes an unevenly distributed RSL time series, prone to vertical and temporal uncertainties, as input and produces estimates of RSL and rates of RSL with 95% credible intervals. The EIV-IGP models rates of RSL change using a Gaussian process (GP) (Williams and Rasmussen, 1996) and models RSL as the integral of the GP (IGP) taking into account vertical uncertainty. Temporal uncertainties are accounted for by setting the IGP model in an errors-in-variables (EIV) framework (Devy et al., 2000). This quantitative approach has been used in several recent papers dealing with RSL change (e.g. Kemp et al., 2011, 2013; 2015; Shaw et al., 2018) providing data which can further be reliably compared (e.g. Kemp et al., 2015).

4.4. Periods of rapid climate change

Periods of rapid climate change are not uniform across the Mediterranean (Lionello, 2012; Luterbacher et al., 2012), so the selected ages have been chosen according to the classic climatic historical events defined in the literature (i.e. Hass, 1996; Trouet et al., 2009; Nieto-Moreno et al., 2011, 2013; Moreno et al., 2012; Lirer et al., 2014); Roman Period (RP, from 123 BC to 470 AD), Dark Ages Cold Period (DACP; from 470 until 900 AD) (also called Early Middle Ages), Medieval Climate Anomaly (MCA, from 900 to 1300, and Little Ice Age (LIA, from 1300 to 1850 AD) and with the Current Warm Period as the most recent period. The LIA period has been divided into two intervals, an early relatively warmer interval (LIA I) and a later colder interval (LIA II) by reference to Cisneros et al. (2016), but the boundary has been defined according to the break in the algal growth which occurred at around 1600 AD.

4.5. Radiocarbon and stable isotope analyses

Samples were labelled, cleaned and dried. They were cut with a diamond saw in the Laboratory of Physical Geography at the Department of Geography, Faculty of Science, University of Zagreb, and then dated by the ^{14}C method in the Radiocarbon Laboratory at the Rudjer Bošković Institute in Zagreb. Two ^{14}C techniques were used for dating algal and shell samples: 1) liquid scintillation counting (LSC Quantulus 1220) using a benzene synthesis method for sample preparation (Horvatinčić et al., 2004) (for the first samples) and 2) accelerator mass spectrometry (AMS) using the graphite sample preparation method in the Radiocarbon Laboratory in Zagreb (Krajcar Bronić et al., 2010) and ^{14}a measurement of graphite targets on AMS in the University of Georgia, Center for Applied Isotope Studies, USA (Cherkinsky et al., 2010).

In total, 47 samples from the algal rims and mollusc shells (mainly bivalves - *Mytilaster lineatus* (Gmelin, 1791) and *Lasaea adansoni* (Gmelin, 1791)) were dated, 22 by the LSC method and 25 samples by the AMS method. The results were reported as a percent of modern carbon (pMC) and conventional radiocarbon age in ^{14}C years BP (Stuiver and Polach, 1977). The ^{14}C ages were corrected for isotope fractionation using the δ^{13}C values measured by IRMS and normalized to −25‰ VPDB (Stuiver and Polach, 1977). The stable isotope composition (δ^{18}O ‰ VPDB and δ^{13}C) of the samples was analysed at the Joanneum Research Laboratory, Institut für Angewandte Geowissenschaften in Graz (Austria), at the University of Melbourne (Australia), and at the University of Georgia, Center for Applied Isotope Studies (USA).

The ages were calibrated with the standard MARINE13 calibration curve (Reimer et al., 2013) and the regional average marine reservoir correction (ΔR) for the Adriatic Sea (Faivre et al., 2015, 2019).

4.6. Reservoir ages

Previous research assumes that the rim building alga *Lithophyllum byssoides* does not appear to be subject to any kind of reservoir effect (Laborel et al., 1994). This assumption was based on the dating of living *thalli*. Considering the time scale of this study (1.5 ka), the ^{14}C reservoir effect may have an important influence on the final ^{14}C results. So, we engaged different studies in order to find out about the marine reservoir effect (MRE) of the algae and shells in the Adriatic (ΔR) (Faivre et al., 2015) and of the intertidal alga *L. byssoides* from direct measurement in the Mediterranean and in the Adriatic (Faivre et al., 2019).

The corrections of MRE (and local ΔR) are fundamental (Alves et al., 2018), particularly for late Holocene sea-level and palaeoenvironmental chronologies and, above all, when such data are further compared with archaeological data based on other chronologies as is often the case in studies of RSL changes. Consequently, the analysed data were corrected for MRE by means of the study of samples of known age from museum collections. Samples of pre-bomb intertidal alga *L. byssoides* from the Adriatic revealed a mean reservoir age of R(t) 318 ± 35 ^{14}C yr and a ΔR (weighted mean) value of −47 ± 35 ^{14}C yr (Faivre et al., 2019) while shells in the Adriatic reveal larger variations. Here we calibrated shell data using the Adriatic mean, i.e. the ΔR of 77 ± 57 ^{14}C yr (Faivre et al., 2015).

5. Results

5.1. Algal rims

Two algal structures have been studied on the southern coast of Istria at Premantura (structures A and C; Fig. 3). The Premantura structure A is a classical well-developed *Lithophyllum* rim of small size (considering the largest Mediterranean structure is about 2 m wide (Laborel et al., 1994) and 1.8 m in the Adriatic (Faivre et al., 2013)). It has one upper, pronounced level, around 3 m long which is up to 40 cm wide (Fig. 3a). The Premantura structure C is an angular structure (Fig. 3d) the morphology of which is partly related to the sub-horizontal layers of the Cretaceous limestone substrate. Structure C has a maximum width of 80 cm and is around 4 m long. Algal rims start to form at a depth of around 50 cm below the MSL even though fossil *Lithophyllum* have also been sampled slightly below the rim.

Along the eastern coast, algal rims have been observed at two locations; Uboka and Brseč (Fig. 1). Both algal rims are very small in size, around 2 m long and 20 cm wide (Fig. 4). In the Brseč area, the rim is an angle type but it is not related to the structural properties of the substrate (Fig. 4d). The most protruding parts of both rims

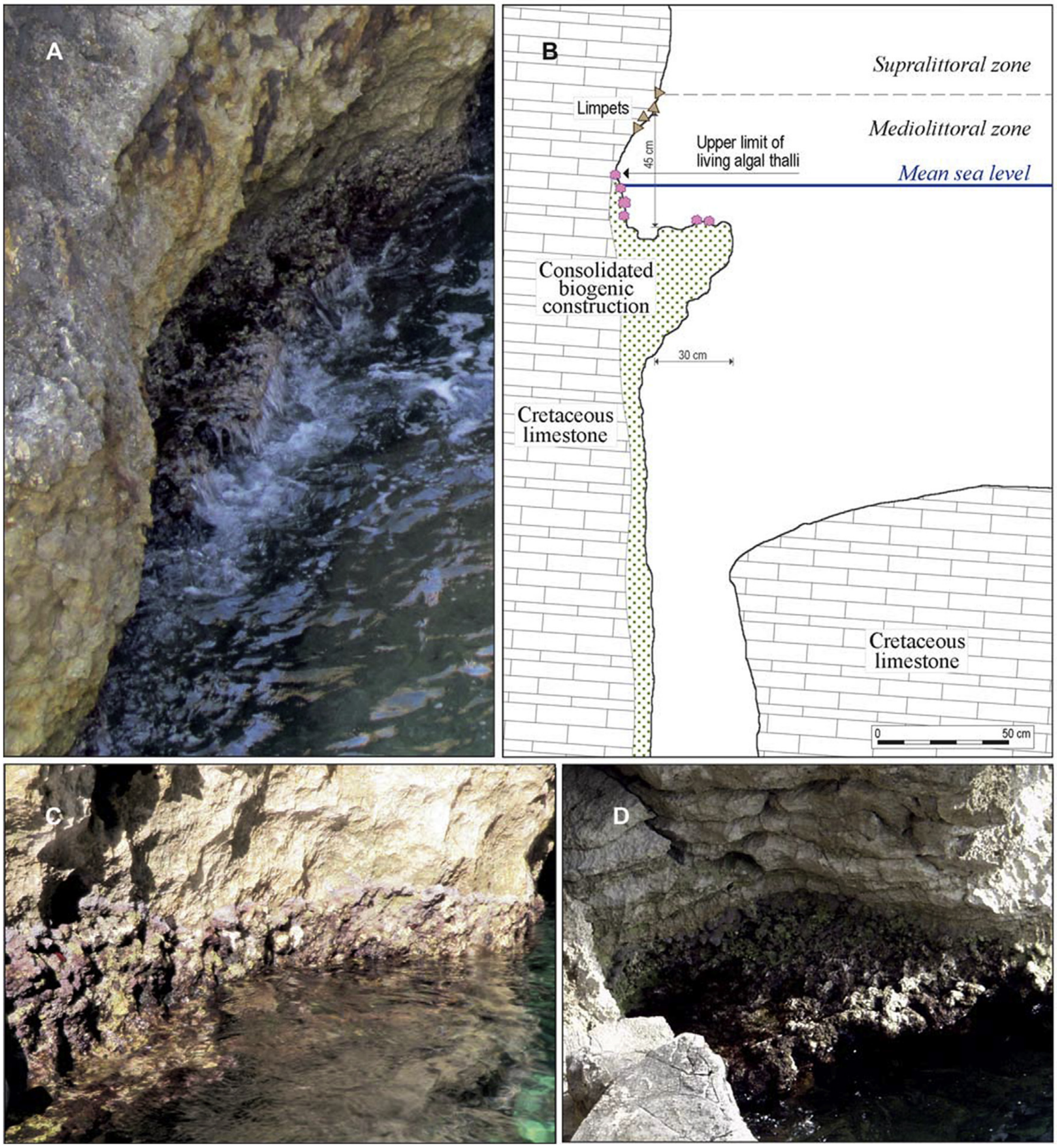

Fig. 3. Algal rims on the southern coast of Istria, at the Premantura site; a) cross section of structure A, b) structure A, c) row of living thalli on structure A d) structure C.

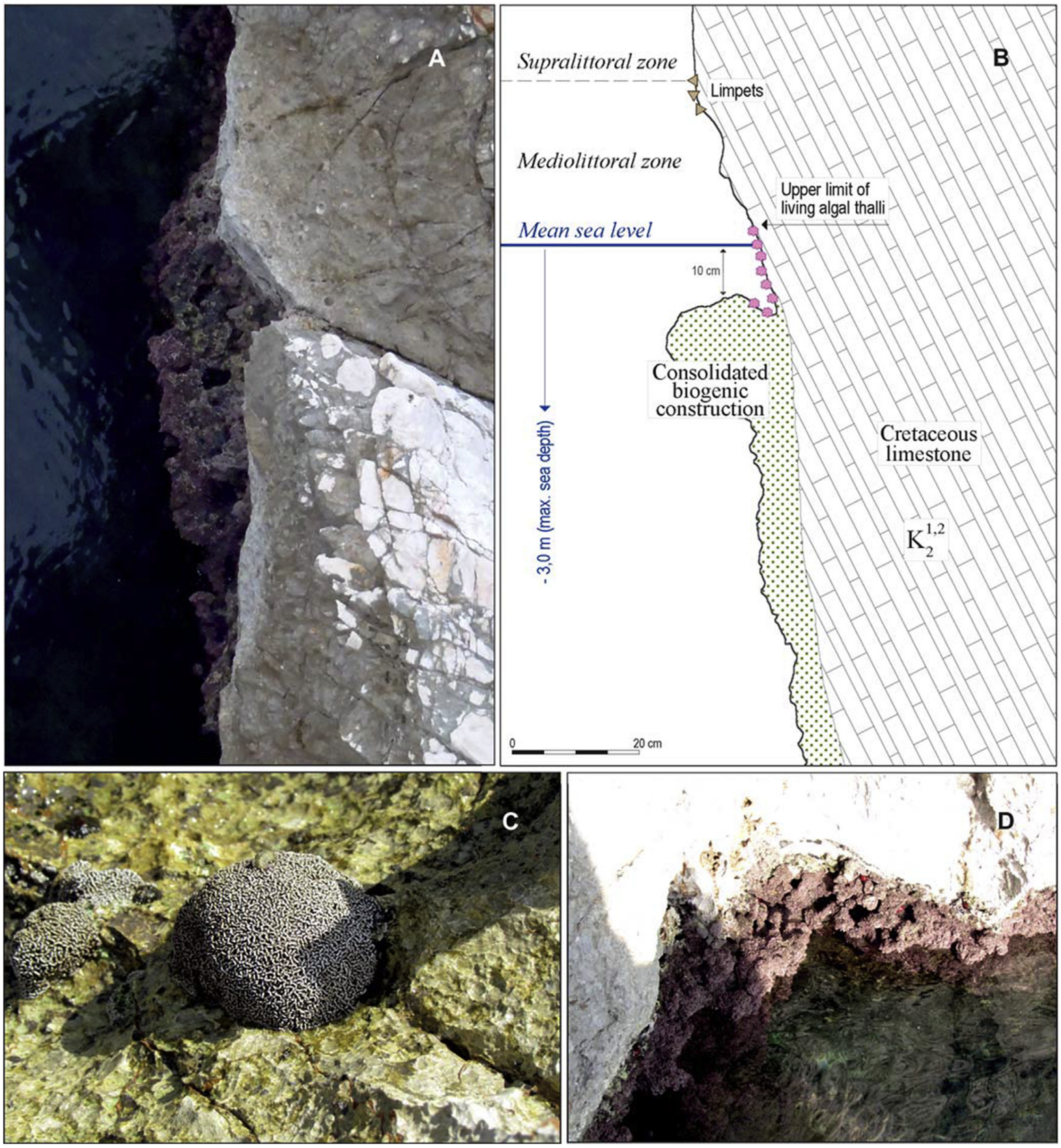

Fig. 4. Algal rims on the eastern coast of Istria at the Uboka and Brseč areas; a) cross section of the rim at Uboka bay, b) the rim at Uboka bay, c) living thalli at Uboka bay, d) algal rim at the Brseč location.

(the largest parts) are presently around 10 cm below the current MSL.

The ^{14}C dating of algal rims reveals the long term RSL change of 0.48 mm/yr during the last 1550 years at the Premantura site (Fig. 5, Tables 1 and 2). However, changing RSL showed important variations during the centuries. The data reveals four general phases of RSL change. During the DACP (from AD 400 till 800) until the first part of the MCA, RSL was generally stable (Fig. 5). The minor variability is within the range of vertical uncertainty of the data. After AD 800, during the MCA, RSL rose at rates of ~0.5–0.8 mm/yr until around AD 1400 (the MCA-LIA transition). The maximum rates of increase of 0.81 mm/yr (0.6–1.1 mm/yr; 95% credible interval) were determined between AD 1129–1161 (Fig. 6a). These quantitative data were obtained from the EIV-IGP model based on the total data set (Fig. 6). During LIA I (~AD 1400 till 1600) the rate of RSL change slowed. This relative stability allowed the rims at the Premantura area to reach widths of ~40–80 cm at their uppermost parts (structures A and C respectively; Figs. 3 and 5). The major rim building phase ended after AD 1600 in the Premantura area. The most protruding parts of the algal rims are presently 13–15 cm below MSL.

Along the eastern coast of Istria, two structures formed between AD ~1400 and 1900 in the Uboka area and from AD ~1500 and 1800 in the Brseč area (Fig. 5; Table 1). The largest part of both rims relates to the LIA I period. Between AD ~1600 and 1750 algal rims in the study area did not form what roughly corresponds to the colder LIA II interval (Fig. 5). Small differences between the Brseč and Uboka areas could be also related to the difference in exposure, as Brseč is located on an exposed site while Uboka is located in a more sheltered location.

Observations on the algal rims suggest that the RSL started to rise again from the 19th century. Historical records from the nearby

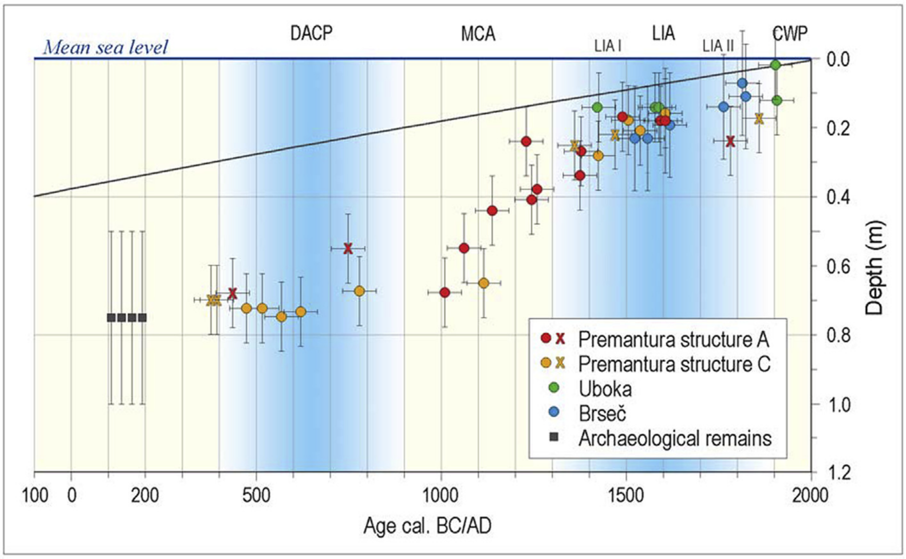

Fig. 5. The 1.5 ka relative sea-level change based on algal samples (circles) and shell samples from the rims (x) and the predicted model (black line) of RSL change for the Northern Adriatic from Lambeck et al. (2011). Submerged archaeological records from the western coast of Istria are according to Faivre et al. (2010b), Fouache et al. (2011) and Rousse et al. (2013).

Table 1
Radiocarbon dates obtained on *Lithophyllum byssoides* samples from Premantura (P), Brseč (B) and Uboka (U) rims. Measured ^{14}C activity is expressed as percent of modern carbon (pMC) for modern samples. The ages were calibrated with the standard MARINE13 calibration curve (Reimer et al., 2013) and the regional average marine reservoir correction (ΔR) for *L. byssoides* from the Adriatic Sea (ΔR of −47 ± 35 ^{14}C yr; Faivre et al., 2019). Calibrated ages (cal AD) are expressed as 95.4% probability intervals and median values of respective age distributions.

No.	Lab. No	Sample ID	Depth below MSL (cm)	$\delta^{13}C$ (‰) (VPDB)	$\delta^{18}O$ (‰) (VPDB)	^{14}C age (yr BP)	Cal ^{14}C age AD (Median)	Calibrated range (cal AD), 2 σ
Premantura								
1	Z-5383	P0a– *living thalli*	0	−3.7	–	*103.17 ± 0.27 pMC*	2013	–
2	Z-5382	P0– *living thalli*	0	−0.88	−1.39	*101.50 ± 0.62 pMC*	2013	–
3	Z-5385	P_1A7	17	2.33	2.03	785 ± 49	1490	1406–1636
4	Z-5386	P_1A8	18	2.0	–	667 ± 20	1590	1503–1672
5	Z-6008	P_1A8_A	18	2.0	–	643 ± 22	1608	1518–1688
6	Z-5156	P_1A1	24	2.46	−0.45	1116 ± 75	1229	1057–1360
7	Z-5161	P_1A6	27	2.04	−1.24	935 ± 46	1376	1294–1457
8	Z-5160	P_1A5	34	2.19	−0.48	941 ± 48	1372	1290–1456
9	Z-5159	P_1A4	38	2.34	−0.25	1088 ± 51	1258	1132–1391
10	Z-5158	P_1A3	41	2.24	−0.63	1108 ± 49	1242	1089–1338
11	Z-5157	P_1A2	44	2.45	−0.90	1220 ± 50	1138	1026–1267
12	Z-5162	P_2A1	55	2.26	−0.73	1300 ± 47	1062	921–1197
13	Z-5388	P_3A2	68	2.5	–	1346 ± 21	1009	903–1113
14	Z-5390	P_1C6	16	2.36	2.22	648 ± 49	1602	1475–1710
15	Z-5391	P_1C7	18	2.24	2.03	770 ± 49	1503	1420–1641
16	Z-5168	P_1C4	21	2.32	0.01	731 ± 34	1534	1455–1645
17	Z-5167	P_1C3	28	2.36	−0.45	871 ± 44	1422	1322–1501
18	Z-5392	P_2CI	65	2.23	2.1	1248 ± 92	1111	909–1292
19	Z-5169	P_2CII1	75	2.48	−0.23	1786 ± 54	568	428–685
20	Z-5170	P_3CI1	73	2.34	−0.20	1733 ± 53	619	458–733
21	Z-5171	P_3CI2	67	2.14	−0.28	1575 ± 95	777	589–999
22	Z-5393	P_3CII6	72	2.0	–	1884 ± 21	472	365–581
23	Z-6011	P_3CII6_A	72	2.0	–	1839 ± 23	516	418–623
Uboka								
24	Z-5175	U_0 – *living thalli*	0	−3.13	−1.74	*102.74 ± 0.69 pMC*	2012	–
25	Z-5176	U_1	14	1.48	−0.55	685 ± 58	1576	1459–1688
26	Z-5177	U_2	14	1.81	−0.55	667 ± 52	1588	1471–1694
27	Z-5394	U_3	14	1.37	1.66	874 ± 51	1419	1314–1507
28	Z-5395	U_4	12	1.91	1.68	75 ± 86	1906	1885–1950
29	Z-6632	U_x	0	1.26	–	209 ± 62	1912	1845-modern
Brseč								
30	Z-6541	B_5a	6	1.53	1.03	461 ± 22	1816	1704–1910
31	Z-6545	B_1i	11	2.06	1.41	457 ± 22	1822	1455–1633
32	Z-6544	B_1g	14	1.99	1.52	508 ± 22	1763	1522–1694
33	Z-6543	B_1d_1	19	1.97	1.82	633 ± 22	1617	1667–1891
34	Z-6546	B_4a	23	1.49	1.52	705 ± 22	1558	1709–1910
35	Z-6542	B_1a	23	2.52	1.59	739 ± 22	1522	1476–1652

Table 2
Radiocarbon dates obtained on shell samples from the Premantura algal rims. The ages were calibrated with the standard MARINE13 calibration curve (Reimer et al., 2013) and the regional average marine reservoir correction (ΔR) for shells from the Adriatic Sea (ΔR of 77 ± 57^{14}C yr; Faivre et al., 2015). Calibrated ages (cal AD) are expressed as 95.4% probability intervals and median values of respective age distributions.

No.	Lab. No.	Sample ID	Depth below MSL (cm)	δ^{13}C ‰ (VPDB)	^{14}C age BP	Cal^{14}C age AD (Median)	Calibrated range (cal AD), 2 σ
1	Z-5172	P_3CII3- shell	−72	0.84	2084 ± 23	377	227–549
2	Z-5173	P_3C II 4 shell	−72	1.31	2073 ± 21	391	303–466
3	Z-5164	P_3A – shell	−68	−0.73	2039 ± 24	434	271–583
4	Z-5163	P_2A2 – shell	−55	1.48	1718 ± 23	750	643–897
5	Z-5166	P_1C2 – shell	−28	1.74	1089 ± 23	1359	1273–1450
6	Z-5389	P_1C5 – shell	−18	2.5	533 ± 21	1859	1720–1950
7	Z-5165	P_1C1 – shell	−21	1.07	937 ± 23	1467	1343–1593
8	Z-6009	P_1A9_a shell	−18	2.4	533 ± 22	1859	1720–1950
9	Z-6010	P_1C5_A-shell	−16	2.2	534 ± 23	1858	1719–1950
10	Z-5387	P_1A9 – shell	−18	5.2	617 ± 26	1784	1673–1910
11	Z-6012	P_1A10_shell	−18	1.9	586 ± 22	1813	1697–1950
12	Z-6013	P_1A9_b shell	−18	1.1	1335 ± 22	1146	1032–1271

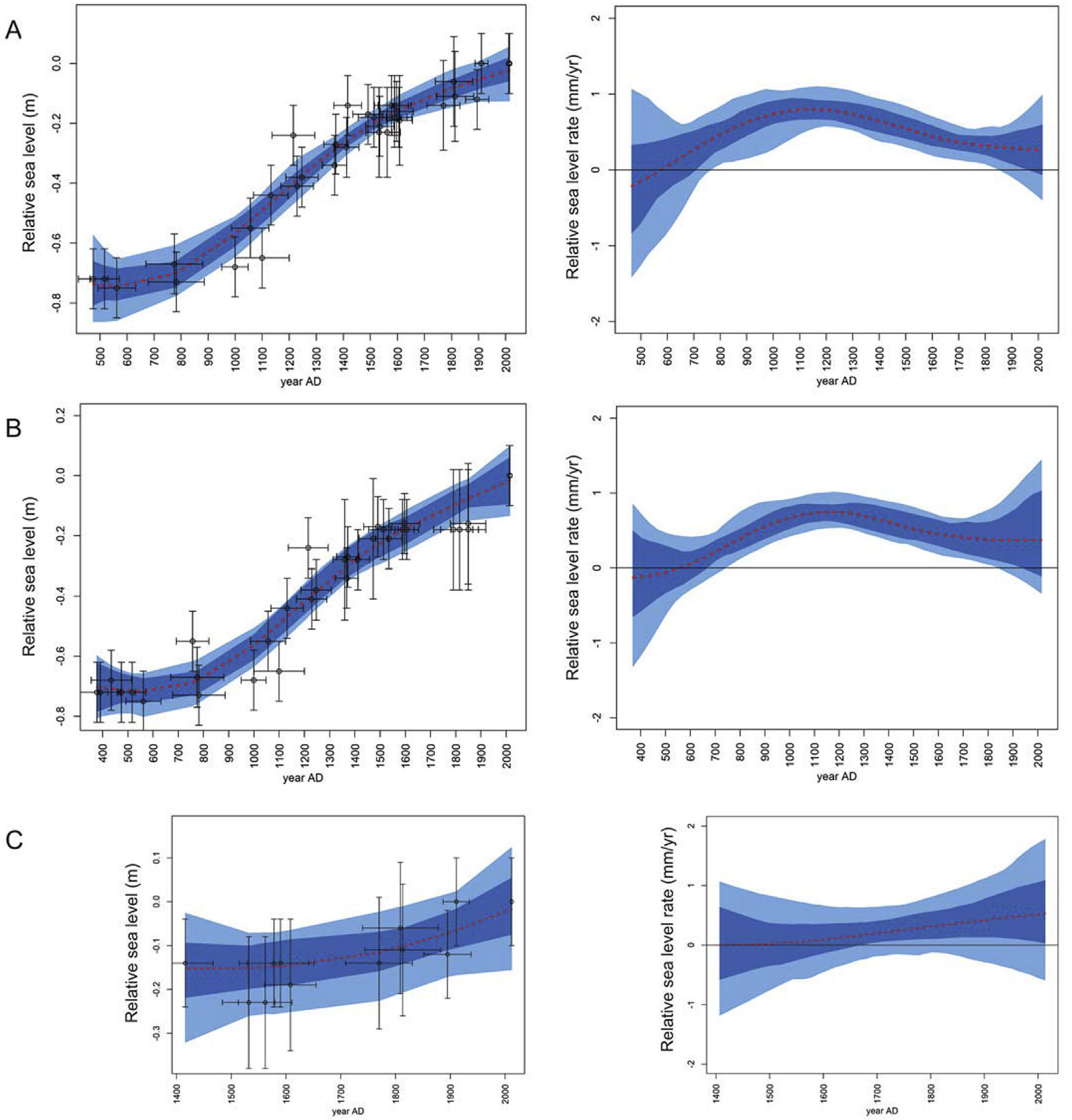

Fig. 6. The age depth model of relative sea-level change along the Istrian peninsula, EIV-IGP model predictions (mean (dashed red lines) with 68% (dark blue) and 95% (light blue) credible intervals); right-side panels show estimated rates of RSL change – A) for Istria (all sites), B) for the Premantura site (*alga and shell dataset*) and C) for the Uboka and Brseč areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

island of Krk (Fig. 1) provide additional information on RSL rise over the larger Kvarner area. St. Mary's monastery and Church (Glavotok area, Fig. 1) was built at the beginning of the 16th century. The church was enlarged in the 17th and the monastery renovated in the 18th century but in 1879, according to the church archive, the western part of the monastery was dislocated more inland due to the high wave impact. This fact allows the assumption that acceleration of sea-level rise in the Kvarner area probably started in the second part of the 19th century (1860–1870). This obviously corresponds to the beginning of the warming and to a sea-level rise from around 1860 as depicted from different global sources (e.g. Jevrejeva et al., 2008).

If the RSL data obtained from the Istrian peninsula are compared with the glacial-isostatic model predictions for the northeastern Adriatic from Lambeck et al. (2011), it is clear that the measured data from the rims revealed lower than the modelled data (Fig. 5). This is even more pronounced in the case of the ICE-7G_NA (VM7) glacial-isostatic model of Roy and Peltier (2018). Thus, except for the applied corrections for crustal movements associated with the ongoing glacial isostatic adjustment (GIA) of 0.188 mm/yr according to Lambeck et al. (2011) we further subtracted an additional rate of subsidence of 0.2 mm/yr, i.e. 0.388 mm/yr in total (Fig. 7), and removed the complete estimated land-level component expressed relative to AD 1400–1600 averages, a period of RSL stability when algal rims increased in size (used as a reference level).

The new modelled land-level adjusted sea-level curve confirms the four major phases of RSL change (Fig. 8). The first period reveals a change from a sea-level drop which lasted until the AD 782–813 to sea-level rise which culminated during AD 1129–1161 and importantly slowed down after AD 1319, but persisted until 1604–1635 (with rates of ~0.1 mm/yr). The LIA II interval reveals a sea-level drop from 0.0 to −0.1 mm/yr until 1888–1920 when the sea-level started to rise again. During this latest period of RSL rise (Fig. 5) the data are sparse as it is not favourable to the rim building processes (Faivre et al., 2013); consequently, in this latest period the confidence level of the model decreases and precision is reduced (Fig. 8). The data obtained directly from the algal rim geochronology and morphology are more precise in this case.

5.2. Tidal notch formation - periods of relative sea-level stillstand

The tidal notches, indentations into a hard substrate, along the western Istrian coast have been principally observed along the steep rocky segments of the coast e.g. along the Limski channel, Verudica cape, and St. Polo (Fouache et al., 2000). This is also the case at Premantura (Fig. 9). The tidal notches studied at the Premantura site are presently 70 cm below MSL with an inward depth of ~50 cm testifying to the relatively long RSL stability period. The two sea-level markers, algal rims and tidal notches are from exactly the same location, both on rocky coast, giving thus firm predisposition for their correlation.

5.3. Stable isotopes δ^{18}O and δ^{13}C – palaeoenvironmental reconstruction

The increasing use of coralline algae as archives of paleoclimatic information over the past decade is based on the fact that their growth and cell calcification are related to temperature and light variability (Halfar et al., 2011). The strong temperature dependence of coralline algal δ^{18}O ratios was demonstrated in comparison with regional sea surface and air temperatures, and with Mg/Ca ratios measured in the same specimens (Halfar et al., 2008; Hetzinger et al., 2009). However, *Lithophyllum byssoides* does not form annual growth increments so the direct correlation with a modern *L. byssoides* cannot be made. However, *L. byssoides* deposits carbonate in isotopic equilibrium with ambient seawater (Faivre et al., 2019), so that δ^{18}O could be used here as a palaeotemperature (palaeo climate) proxy.

In the study area, the δ^{18}O records (Fig. 10) range from −1.7–2.2‰ VPDB (Table 1). The significant variations of the algal δ^{18}O were observed between ~ AD 1400–1600 which mostly corresponds to the LIA I interval, revealing it to be a very unstable period. The heaviest δ^{18}O value of 2.2‰ relates to the end of the LIA I interval and the beginning of the LIA II (Fig. 10; Table 1). The whole LIA II interval exhibits relatively enriched δ^{18}O values while recent δ^{18}O records (from living thalli) show a significant actual depletion.

The *Lithophyllum byssoides* δ^{13}C record ranges from −3.7–2.5‰ VPDB (Fig. 10, Table 1). Before the modern period (CWP), δ^{13}C

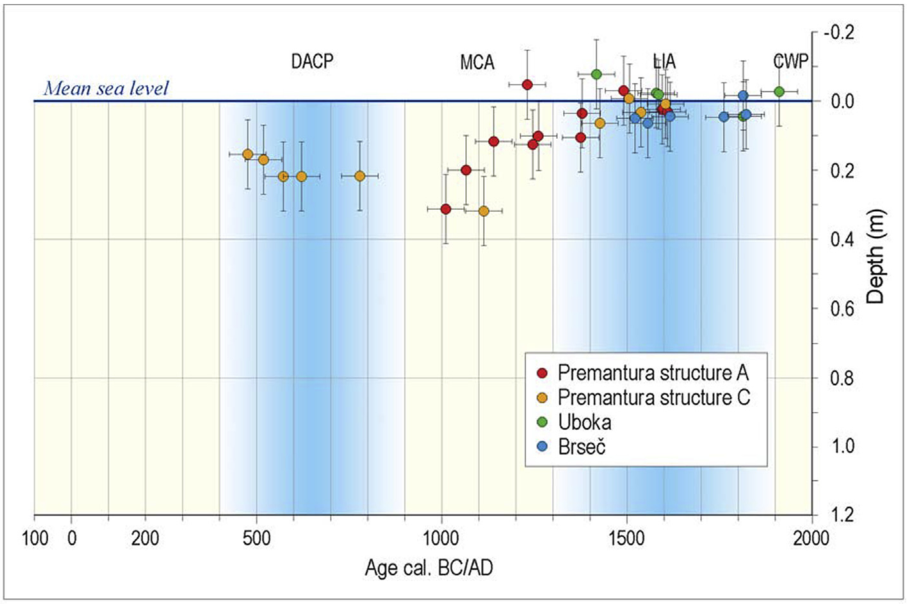

Fig. 7. Land-level adjusted sea-level change.

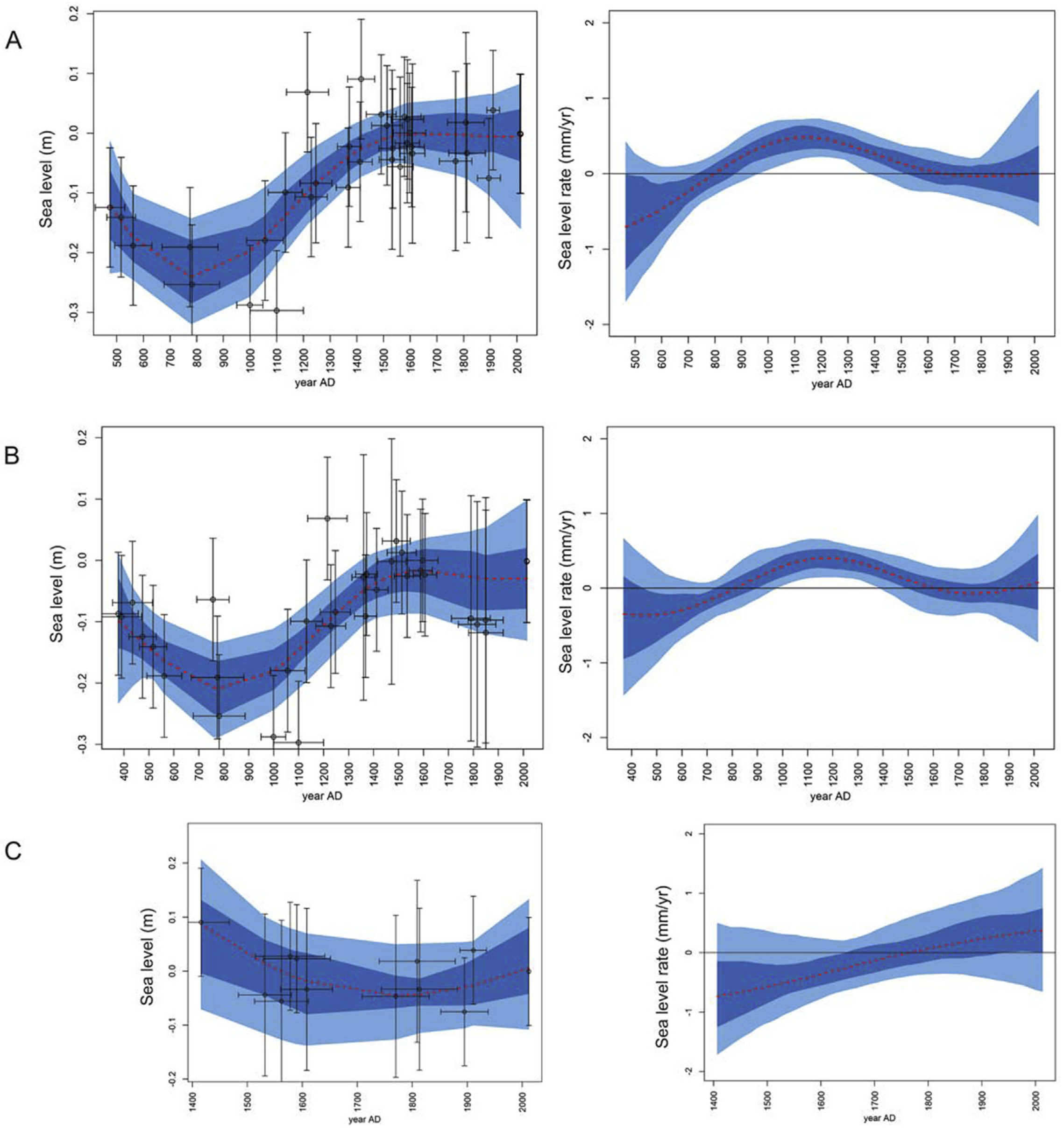

Fig. 8. Land-level adjusted sea-level change, along the Istrian peninsula, EIV-IGP model predictions (mean (dashed red lines) with 68% (dark blue) and 95% (light blue) credible intervals); right-side panels show estimated rates of sea-level change after total land-level correction — A) for Istria, B) for the Premantura site (*alga and shell dataset*) and C) for the Uboka and Brseč area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

exhibits a mean value of around 2.1‰ VPDB. Periodical small depletions occurred during the LIA I and at the end of the LIA II period. The present $\delta^{13}C$ depletion is mostly related to the increased anthropogenic emissions of ^{13}C depleted carbon dioxide and possibly also to a certain decrease in primary production. A very important difference between the *L. byssoides* $\delta^{13}C$ during the preindustrial and the recent period is observed. Recent records exhibit depleted isotopic values that were not measured in the previous 1500 years.

6. Discussion

6.1. Reconstruction of RSL change and climate change from algal rims

The *Lithophyllum* rims developed along the coast of Istria directly point to a near-stable or slowly rising sea-level environment, as for building a well-developed rim, a continuous superposition of new layers upon the dead core that buttresses and strengthens the rim is required (Laborel et al., 1994). Too rapid RSL rise prevents the vertical development of the rim (Faivre et al., 2013).

In the studied areas we observed that all rims increased in size (width) during the RSL stability (or slow sea-level rise) which occurred throughout the LIA I interval (Fig. 5). At the Premantura site, the rims are at a minimum, twice as large as those at the Brseč or Uboka areas. This also suggests that the rim building favourable period lasted at least twice as long on the southern coast compared to the eastern Istrian coast. Moreover, at the Brseč and Uboka areas, the rims do not form prior to LIA I. After the gap during LIA II the small rims continued their growth, reflecting the re-establishment of the appropriate conditions but obviously for a very short time

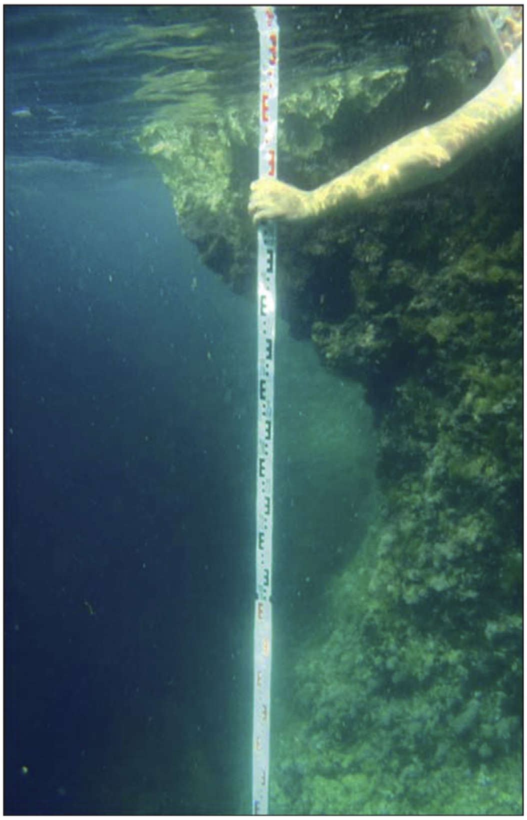

Fig. 9. Tidal notch at the Premantura area.

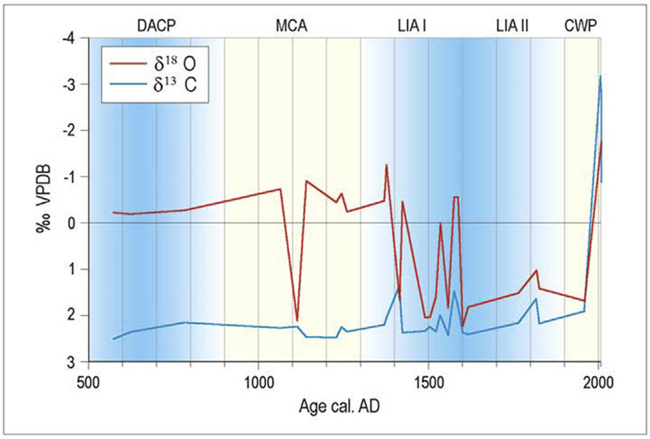

Fig. 10. Variation of *L. byssoides* δ^{13}C and δ^{18}O during 1500 years in Istria.

period as the rims did not increase further in size (width). Consequently, we observed that different morphology of the rims between the southern and eastern coast of Istria, with the same eustatic component, could be the result of different RSL relations connected to different land-level movements between the southern and eastern Istrian coast.

This research reveals that the land-level changes in the Premantura area during the studied period are generated by subsidence of around 0.4 mm/year (regardless of its origin which could be either from GIA and/or tectonics). This subsidence trend has also been recorded in GPS measurements (Altiner, 1999; Serpelloni et al., 2013). Subsidence rates of −0.5 to −1 mm/yr of Serpelloni et al. (2013) along the southern coast of Istria, are close to the rate obtained from the algal rims. For the two other locations (Brseč and Uboka), which are obviously different, the rim sections are too short to enable reliable conclusions at present. However, according to the somewhat slower rates of RSL rise during the CWP and to the higher position of tidal notches (~50–55 cm below MSL, Benac et al., 2004) compared to those from Premantura, it could be argued that the observations reflect a somewhat lower amount of subsidence compared to the Premature area.

Following correction for the estimated total land-level change (0.388 mm/yr) in the Northern Adriatic, we observed that the sea-level fall at a mean rate of −0.4 mm/yr during the DACP and the rapid sea-level rise up to 0.5 mm/yr (0.2–0.8 mm/yr, 95% credible interval) during MCA (Fig. 8). This rapid rise is similar to values obtained by Kemp et al. (2011) for Northern Carolina (Fig. 11). The rapid RSL increase during the MCA period has also been observed in the Central Adriatic at a total rate of ~0.71 mm/yr (Faivre et al., 2013). During the LIA II, the sea-level falls again (mean rate −0.1 mm/yr) (Fig. 8) (similar to Kemp et al. (2011) as well) followed by a sea-level rise during the CWP. Consequently, data from the Northern Adriatic reveal four phases of sea-level change after correction for land-level movements, the MCA – LIA transition being a period of relative stability.

This RSL stability which occurred during LIA I and the most probable RSL drop during LIA II interval (Fig. 8), have also been discerned through the progradation of valleys along the western coast of Istria. Colder climate properties probably enhanced erosion and denudation processes which together with RSL stability, resulted in increased sedimentation rates up to 2.36 mm/y (Faivre et al., 2011a) and progradation of the river mouths (Faivre et al., 2011a; Kaniewski et al., 2016; Benac et al., 2017). This RSL stability seems to be even more pronounced along the Central Adriatic where tidal notch formation was also assigned to the LIA period (Faivre and Butorac, 2018). Likewise, during this stable period, large algal rims (up to 1.8 m) were formed on the Vis, Ravnik and Biševo Islands (Faivre et al., 2013).

Moreover, it is of particular interest that, during the colder LIA II interval in Istria (Fig. 5) algal rims did not form. However, this gap in algal growth could be generally related to either geodynamic conditions, eustatic changes and/or environmental conditions but we assume that the global eustatic component (eustatic sea-level fall) coupled with land-level movements is the major factor for the break in algal rim formation during the LIA II interval in the study area.

This study suggests that δ^{18}O analysis of *L. byssoides* from the Northern Adriatic clearly reflects the global temperature pattern (Fig. 12) and coincides with the global periods of rapid climate change. This is particularly well observed in the LIA chronology distinguishing the LIA I and LIA II intervals. During LIA I, temperatures strongly fluctuate, and during the LIA II interval they significantly drop (Fig. 10) corresponding to the prolonged cooling (~AD 1450–1850) in the Mediterranean region (Luterbacher et al., 2012), with 2 °C and 3 °C colder sea water temperature in the western and the eastern Mediterranean basins, respectively (Sisma-Ventura et al., 2009). Furthermore, recent records reveal depleted δ^{18}O values which agrees well with the general trend of global warming (e.g. Mann and Jones, 2003; Mann et al., 2008). This could be clearly observed in comparison with the vermetid δ^{18}O records from the Tyrrhenian Sea (Silenzi et al., 2004) and the Israeli coastal plain (Sima-Ventura et al., 2009) (Fig. 12). The vermetid δ^{18}O records from the Tyrrhenian Sea are close to the *L. byssoides* δ^{18}O records from the Northern Adriatic (Fig. 12). The obtained data are also comparable to the western Mediterranean Sea surface temperatures reconstructed from a set of multi-proxy records from sediment cores (Cisneros et al., 2016).

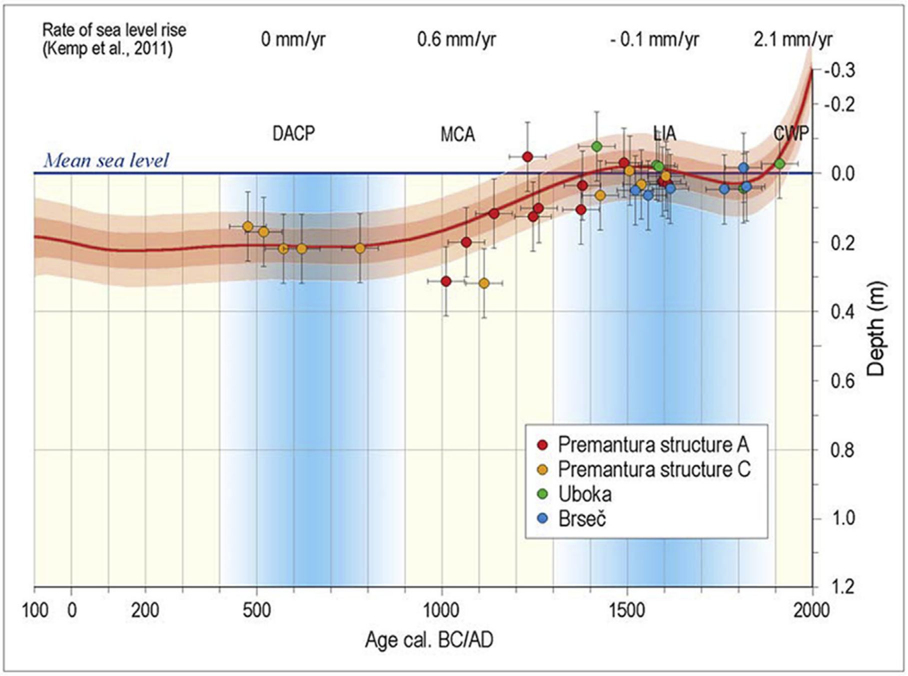

Fig. 11. Comparison of the data from Istrian algal rims with the sea-level curve of Kemp et al. (2011) expressed relative to mean sea-level from AD 1400–1800 and visually summarized by an envelope.

The eastern Adriatic coast and its algal rims belong to the temperate environment, with temperatures in the study area today corresponding roughly to the global means (e.g. the mean air temperature in Pula from 1999 to 2014 was 15.9 °C) (Croatian Meteorological and Hydrological Service). Since algae live in the intertidal zone, we can also compare data from the rims with the sea and air global surface temperature variation curve based on proxy reconstructions of Mann et al. (2008) covering the last 1.5 ka. Consequently, the general temperature dependence of algal $\delta^{18}O$ ratios in comparison with sea surface and air temperatures (Mann et al., 2008) can be observed (Fig. 12).

It is well known that $\delta^{18}O$ variations registered by different organisms can provide an indirect measure of climatic changes (Silenzi et al., 2004; Cisneros et al., 2016). Two potential climate archives were suggested in order to obtain high-resolution records in the Mediterranean region, comparable to the records of tropical corals (Correge, 2006): non-tropical coral *Cladocora caespitosa*, and the vermetid reef builder *Dendropoma petraeum*, a sessile gastropod that developed dense aggregations on the abrasion platform edges (Antonioli et al., 1999; Silenzi et al., 2004). Bioconstructions of *L. byssoides*, can also be included as an additional potential climate archive and can thus provide a preindustrial context for understanding the patterns and causes of contemporary and future climate and sea-level changes.

In the past few years it has become widely accepted that the late Holocene sea-level was nearly stable (near equilibrium) at multi-decadal to multi-centennial timescales until the onset of modern rates of rise in the late 19th or early 20th century (Bindoff et al., 2007; Church et al., 2008; Cronin, 2012). Given the attribution of 20th century sea-level rise to global climate change (e.g. Rahmstorf, 2007), it is reasonable to expect similar phases of sea-level behaviour within the late Holocene related to known phases of warmer, e.g. the Medieval Climate Anomaly, and cooler, e.g. Little Ice Age temperatures (Kemp et al., 2013). Climate-driven centennial sea-level variability superposed on the late Holocene RSL is expressed at the global scale (Kopp et al., 2016) with the transition from the Medieval Climate Anomaly (MCA) to the Little Ice Age (LIA) coinciding with a reduction in air and ocean temperatures (Mann et al., 2009; Marcott et al., 2013; Rosenthal et al., 2017).

Here we observed that in the Northern Adriatic the rates of the RSL change are related to the periods of rapid climate change as also previously find out in the Central Adriatic (Faivre et al., 2013).

6.2. *Modern sea-level rise (CWP)*

The onset of the rapid rise of modern sea-level has been dated to the end of the nineteenth or the beginning of the twentieth century, but variability is evident in both the magnitude and timing of the change; in proxy records as well as in instrumental data (Gehrels et al., 2011; Kemp et al., 2013, 2015).

Based on the algal rim formations from the eastern coast of Istria after a gap of around 150 years (LIA II interval) we observed that small protrusions (segments) of the rims started to form again at the end of the 18th century. This corresponds to the results obtained from the global sea-level reconstruction based on tide-gauge records from 1700, which provided evidence that acceleration in sea-level rise, up to the present, started at the end of the 18th century (Jevrejeva et al., 2008). It seems that the re-initiation of the eustatic component (obviously very slowly) allowed a renewed rim building phase at the Brseč and Uboka areas as well. The change in eustatic conditions coupled with land-level changes obviously produced short periods of RSL stability or slow rise favourable for algal rim formation. So the turning point between the period of RSL fall and re-initiation of the RSL rise occurred in the second part of the 18th century after the LIA II break in algal rim growth.

Algal rim morphology, shows that since the end of the major rim building phase (LIA I) until today, the RSL rose by around 13–15 cm at the Premantura and around 10 cm at the Uboka and Brseč areas. However, RSL acceleration was most probably initiated in the 19th to 20th century transition as estimated from historical records in the Kvarner area. This consequently means that the RSL change began from the CWP and could be estimated to be 1.0 mm/

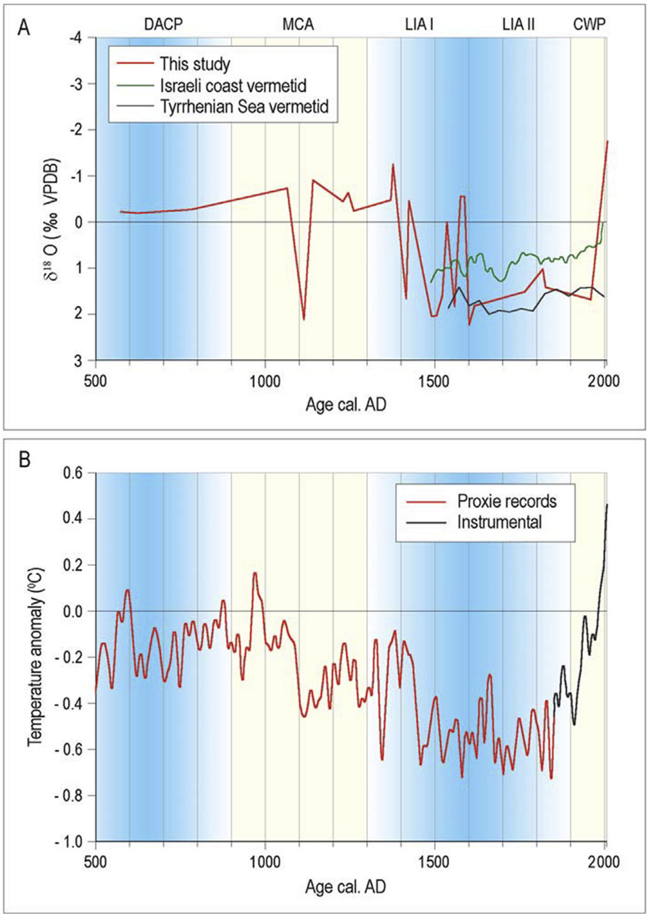

Fig. 12. Comparison of the *Lithophyllum byssoides* δ^{18}O from the Adriatic (Central Mediterranean) with the vermetid δ^{18}O records from the Tyrrhenian Sea (Silenzi et al., 2004) and vermetid δ^{18}O records from Israeli coastal plain (Sima-Ventura et al., 2009) (Fig. 9A) and Mann et al. (2008) temperature anomaly with periods of rapid climate changes (Fig. 9B).

yr along the southern Istrian coast and 0.7 mm/yr along the eastern coast. This corresponds to the findings of Orlić and Pasarić (2000) based on the Rovinj tide gauge data for the period 1955–1995 which concluded a 1 mm/yr rise of the RSL along the coast of Istria and to a ~1 mm/yr rise (1960–2005) at the Kopar tide gauge (Jeromel et al., 2009). According to the long-term Rovinj tide gauge data (1956–2011) the RSL rise amounts to 0.76 mm/yr (Vacchi et al., 2016; PSMSL, 2016).

From the tide gauge data, along the eastern Adriatic, Buble et al. (2010) observed a fairly uniform RSL rise along the coast, with a mean rate of 0.84 ± 0.04 mm/yr. This rate being a factor of 2–4 lower than the estimates for global average sea-level rise.

This is also generally in accordance with the Mediterranean rates of RSL rise for the 20th century obtained from the longest tide gauge records which indicate smaller rates of 1.1–1.3 mm/year (Tsimplis and Baker, 2000; Raicich, 2007; Marcos and Tsimplis, 2008; Tsimplis et al., 2012), compared to the global ones.

6.3. Tidal notches — sea-level during the DACP and RP

Northern Adriatic tidal notches can be generally observed between 0.4 and 0.7 m below MSL (Fouache et al., 2000; Faivre and Fouache, 2003; Benac et al., 2004, 2008; Antonioli et al., 2004, 2007; Faivre et al., 2010b; Furlani et al., 2011a,b). Good preservation of the Northern Adriatic notches has been ascribed to their rapid submersion (Fouache et al., 2000; Benac et al., 2004, 2008; Pirazzoli, 1980, 2005; Antonioli et al., 2007; Furlani et al., 2011a,b; Stiros and Moschas, 2012).

The new RSL data obtained from the algal rims provides an explanation for the enigmatic submerged tidal notch formation in southern Istria. According to the obtained RSL curve based on ^{14}C dating of the fixed biological indicators and notch depth this relatively stable condition could now be precisely related to the ~500 years of temporary sea-level stillstand during the DACP (Figs. 5 and 6) which also corresponds to the estimates of Furlani et al. (2009). The notch was further submerged during the MCA due to RSL rise up to 0.8 mm/yr. The preservation of the notch (the profile is of an elongated shape (Fig. 9), and obviously modified) allows the conclusion that the local rate of intertidal bioerosion is lower than the rates of the RSL rise.

So, even if the intertidal bioerosion rates according to numerous scholars (e.g. Schneider, 1976; Torunski, 1979; Evelpidou et al., 2011; Furlani et al., 2011a,b) reach up to 1 mm/year, the latest data obtained using the micro-erosion meter (MEM) and the traversing micro-erosion meter (TMEM) from the northern Adriatic which indicated that the total mean lowering rates ranged between 0.001 mm/y and 0.260 mm/y (Furlani and Cucchi, 2013), seems to be more realistic for the southern Istrian coast. According to the relatively lower bioerosion rates generally less than 0.3 mm/y it could be assumed that such relatively stable conditions could also have occurred earlier, during the Roman Period.

The data obtained from the algal rims in Istria particularly at the Premantura site do not reveal evidence of co-seismic displacements during the study period. These findings also support the fact that tidal notches can be preserved when submerged without co-seismic events. This was also observed for the Central Adriatic (Faivre et al., 2013) and along the wider Makarska area (Faivre and Butorac, 2018). Likewise, submergence of the Makarska area tidal notches was attributed to the recently accelerated rates of RSL rise, which exceeded bioerosion rates and began around the second half of the 19th century (Faivre and Butorac, 2018). Moreover, similar examples have also been observed recently on several Greek islands (Evelpidou et al., 2012a, 2012b; 2014; Pirazzoli and Evelpidou, 2013) which also confirm the possibility of rapid submergence due to the modern RSL rise (Evelpidou et al., 2012a, 2012b; Pirazzoli and Evelpidou, 2013).

This study allows us to conclude that sea-level during the 4th - 5th century, at the end of the Roman Period, was around 75 ± 10 cm below the present MSL. This roughly corresponds to our first estimates obtained from the correlation of the geomorphological and archaeological markers (Fouache et al., 2000; Faivre and Fouache, 2003).

Results obtained from the algal rims correspond well with those from Melis et al. (2012) who concluded that the sea-level during the Roman period was −0.6 ± 0.2 m lower than present based on the analysis of archaeological remains and sedimentological deposits at two archaeological sites in Trieste. They also suggested that this sector of the Gulf of Trieste has been affected by a vertical tectonic downlift of about −0.2 mm/yr since Roman times.

Submerged archaeological records from the western coast of Istria also attest to sea-level at Roman time being roughly about 1 m lower than the present (Fig. 5) (Faivre et al., 2010b; Rousse et al., 2013; Carre et al., 2019).

Consequently, the chronologies of the eastern Adriatic notches correspond to two major periods of notch formation. Northern Adriatic notches were formed during the DACP and possibly also earlier (during the preceding Roman period), while the Central Adriatic notches have been formed during the LIA period (Faivre et al., 2013; Faivre and Butorac, 2018).

7. Conclusion

This study provides a first high resolution reconstruction of sea-level change and climate change in the Northeastern Adriatic during the last 1.5 ka. Along the coast of Istria, four distinct RSL phases have been distinguished which directly relate to periods of climate change. The RSL was stable during the DACP, increased during the MCA up to ~0.8 mm/yr (0.6–1.1 mm/yr; 95% credible interval) similar to the values obtained previously for the Central Adriatic. The first part of the LIA (LIA I interval) reveals relatively stable RSL conditions, while during the LIA II, as the algal rims do not form, we assume that the RSL most probably fell, as proposed by Kemp et al. (2011) for Northern Carolina. During the following CWP the RSL rose by 13–15 cm on the southern coast and around 10 cm along the eastern coast of Istria, at rates between 0.7 and 1.0 mm/yr similar to the values for the MCA period obtained at the Premantura area and in agreement with data obtained previously from the instrumental records. Removing the land-level movements from the RSL curve showed that the southern coast of Istria has been affected by subsidence (from GIA and tectonic origin) of around −0.4 mm/yr, and thus confirming previous estimations that the southern coast of Istria is a subsiding environment.

Algal rim formations and their morphology directly reflected these different periods of RSL changes. Two different morphologies and evolutionary sequences on the southern and eastern coasts of Istria could point to somewhat different land-level changes for the two coastal segments, which is also supported by their position on two different structural units. However, algal rim morpho-chronological sequences along the eastern coast are too short to enable more precise specification of land-level signals at the moment.

Tidal notches at the Premantura area additionally confirm the existence of the RSL stillstand along the southern Istrian coast, which preceded the sharp RSL increase during the MCA. This stillstand could have lasted for around 500 years or more, as estimated previously, but this study suggests it occurred primarily during the DACP and possibly also earlier. The relative stillstand is probably the result of the coupling of the eustatic sea-level fall during the DACP at a mean rate of −0.4 mm/yr and the land subsidence of up to −0.4 mm/yr. Consequently, this study also provides first explanations for the Northern Adriatic enigmatic notch formation in the subsiding environment, both in terms of when and how the notches formed and when and how the submersion occurred.

The *Lithophyllum byssoides* $\delta^{18}O$ record clearly coincides with the local and global periods of rapid climate change, distinguishing particularly well the different intervals of the LIA (LAI I and LIA II). LIA II is characterised by the overall cooling of surface waters immediately followed by the strongly expressed recent warming in the Central Mediterranean. So coralline alga *L. byssoides* is clearly controlled by environmental factors for which isotopic signatures are good proxies for reconstructing the last 1500 years of Mediterranean palaeo-environments. *L. byssoides* as well as other coralline algae are promising precise marine climate archives with the potential to yield numerous environmental records from regions where other biogenic proxy archives are absent.

This study shows that fixed biological indicators are one of the best RSL indicators and confirm the close link between climate and sea-level changes. The major importance of the *Lithophyllum byssoides* study relies on the ability of its bioconstructions to provide the preindustrial context, that is, the most precise palaeo RSL data on microtidal rocky coasts, and the assessment of vertical land-level movements. This allows future estimates to be made which are today one of the major subjects in the scientific research due to the climate change impacts on densely inhabited Mediterranean coasts.

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